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Magnetospheric energy budget and the epsilon parameter

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[1] Determination of the energy input for the magnetospheric energy budget is a nontrivial matter. As no direct means to measure the input are known, various solar wind-derived proxies have been developed. In this article we discuss one of the most widely used energy input functions, the so-called epsilon parameter of Akasofu. While practice has shown it to be a very useful parameter, there is no convincing evidence that it is superior to all other coupling parameters. Furthermore, its somewhat unclear definition and lack of physical foundation sometimes lead to confusing interpretation of the parameter in practical studies of magnetospheric energy cycle. For example, the parameter is sometimes understood to describe the transfer of solar wind Poynting flux into the magnetosphere, whereas the actual physical energy transfer involves conversion of solar wind kinetic energy to magnetic energy measured inside the magnetopause. Another questionable interpretation is to relate the size of the energy transfer region to the length of the reconnection line, as the scale factor in epsilon has the physical unit of area. These confusions may partly result from mixing the concepts of energy source and energy transfer. In spite of these problems the present empirical formulation of the epsilon parameter appears, from the global energy budget point of view, to give a remarkably good estimate for the total energy input into the inner magnetosphere in substorm and storm timescales. This is even more remarkable as after the parameter was first formulated we have learned that the ionosphere is a major sink of storm and substorm energy, exceeding the ring current in importance as an energy output channel. An additional issue is the energy carried away by the plasmoids and outflow of the postplasmoid plasma sheet. One can argue that the application of epsilon should be restricted to the energy consumption in the inner magnetosphere. However, as the intermittent plasmoid releases are essential parts of the same complex of processes as the ring current enhancement and ionospheric particle injections, we argue that they should be included in the energy budget, even if that might result in rejection of the epsilon as a useful input parameter. The recent analyses of energy output suggest that we can still use epsilon by scaling the parameter up by a factor of 1.5–2. It should be noted, however, that this energy budget does not account for all energy passing through the magnetosphere but only that part which is consumed in the storm and substorm processes. *INDEX TERMS:* 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736); 2788 Magnetospheric Physics: Storms and substorms; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* energy budget, energy conversion, energy input functions, epsilon parameter, Poynting vector, magnetospheric energy dissipation

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1. Introduction

[2] Studies of magnetospheric energy budget, ranging from very long time scales [e.g., *Stamper et al.*, 1999] down to storm and substorm timescales [e.g., *Knipp et al.*, 1998; *Lu et al.*, 1998; *Chun et al.*, 1999; *Kallio et al.*, 2000; *Tanskanen et al.*, 2002a; N. E. Turner et al., Global energy partitioning during magnetic storms, submitted to *Journal*

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of Geophysical Research, 2002, hereinafter referred to as Turner et al., submitted manuscript, 2002], have gained renewed popularity during the last few years. An important motivation for the long-time studies has been to look for a possible relationship between the recently found growth of both the solar magnetic field and irradiance [*Lockwood et al.*, 1999; *Solanki and Fligge*, 1999] and the global terrestrial warming during the last century. In the short-time regime the emerging space weather activities together with improved means of estimating the energy dissipation and conversion throughout the coupled magnetosphere-ionosphere system have contributed to the growing interests in the energetics of the system.

[3] At present, there are no direct observational means of determining the energy transfer from the solar wind to the magnetosphere. In fact, we do not even know the details of how and where the transfer takes place. We know that the efficiency of the transfer is strongly coupled to the southward component of the interplanetary magnetic field (IMF), which indicates that magnetic reconnection at the dayside magnetopause plays a crucial role in the energy transfer. As the steady state reconnection rate is related to the dawn-to-dusk directed component of the solar wind electric field, the product of the solar wind speed and the southward component of the IMF, vB_s [*Burton et al.*, 1975], has turned out to be one of the most useful coupling functions. However, as reconnection itself mostly consumes magnetic energy, the energy transfer process is more global, involving the magnetotail boundary and, very likely, time-dependent "reconnection-dynamo" aspects of the solar wind-magnetosphere coupling.

[4] In the absence of rigorous ways of computing the energy input, the need to have useful estimates of energy available for magnetospheric dynamics has led to the formulation of a large number of coupling functions (for a review, see *Gonzalez* [1990]), of which vB_s and the epsilon parameter discussed in the present study are the most widely used. The different input parameters have been correlated with different ionospheric and magnetospheric indices or proxies of energy consumption. Depending on the data sets used, the underlying assumptions, and also the time-scales under consideration, different functions have turned out to have better or worse correlations during different events or under different statistical approaches [see e.g., *Gonzalez et al.*, 1989; *Wu and Lundstedt*, 1997; *Stamper et al.*, 1999]. In a review paper, *Gonzalez* [1990] argued that all the widely used coupling functions can be derived as particular cases of general expressions for the electric field and energy transfer at the magnetopause due to large-scale reconnection.

[5] In the present study we focus on the energy input parameter that was the result of Akasofu's search, during the 1960s and 1970s, for some "unknown" quantity in the solar wind which would be responsible for the energy transfer to the magnetosphere [e.g., *Akasofu*, 1996]. The search lead to the epsilon (ε) parameter which depends on the solar wind speed v, the IMF intensity B, and the so-called clock angle θ of the IMF orientation perpendicular to the Sun-Earth line, i.e., $\tan\theta = B_y/B_z$ [*Perreault and Akasofu*, 1978; *Akasofu*, 1979, 1981]. (Note that in the original articles the coordinate system was not defined clearly, but in practice the GSM coordinates have become the standard.)

[6] The ε parameter is usually given in the cgs unit erg/s as

$$\varepsilon(\mathrm{erg/s}) = vB^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2 \qquad (1)$$

where the variables in the right-hand side are given in cgs-Gaussian units. We prefer in this discussion the SI units, when the above expression is written as

$$\varepsilon(\mathrm{W}) = \frac{4\pi}{\mu_0} vB^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2 \qquad (2)$$

where the variables on the right-hand side are given in SI units and the numerical value of $4\pi/\mu_0 = 10^7$. The factor l_0 is an empirically determined scale factor with the physical dimension of length. It is scaled to numerically correspond to the estimated energy output in the magnetosphere and the physical dimension of power for the energy input rate. The factor $(4\pi/\mu_0)$ vB^2 corresponds to 4π times the Poynting flux per unit area, i.e., the absolute value of the Poynting vector $\mathbf{E} \times \mathbf{B}/\mu_0$, calculated from the upstream solar wind parameters and assuming that the magnetic field is perpendicular to the velocity. From the formulation of ε we see that the dependence on θ is the strongest, and the dependence on v is the weakest. The solar wind density is not reflected in this parameter at all.

[7] Except for the numerical value of l_0, the functional form of the parameter can be motivated by dimensional reasoning: The power is the solar wind electromagnetic energy flux through an effective area. Another justification was based on reconnection modeling by *Kan et al.* [1980] who considered a voltage drop across a bundle of field lines opened by reconnection. In this analysis the energy transfer to the magnetosphere was assumed to take place through a generator ($\mathbf{E} \cdot \mathbf{J} < 0$) acting on the tail lobe magnetopause over a distance of 200 R_E (Earth radii).

[8] *Perreault and Akasofu* [1978] and *Akasofu* [1979, 1981] estimated the energy output as the sum of total energy output assuming that the main energy sinks are the ring current, auroral Joule dissipation, and particle precipitation to the ionosphere. The scaling factor was found to be $l_0 = 7$ R_E and this value has been used, without any revision, ever since 1981. Following *Akasofu* [1981], input power exceeding 10^{11} W (100 GW) can be considered a substorm level, i.e., if this input exists for some time, a substorm is likely to occur. In magnetic storms the input exceeds 10^{12} W and may intermittently reach up to 10^{13} W.

[9] Note that these estimates display the energy consumed in the inner magnetosphere only. Calculating the tangential stress of the solar wind on the magnetotail, *Siscoe and Cummings* [1969] estimated that the maintenance of the magnetosphere requires a power of $1.2 \cdot 10^{12}$ W. Noting that they used somewhat low values for the average parameters, this argument implies a total energy input rate of a few times 10^{12} W. As this is more than an order of magnitude larger than the typical substorm level in the inner magnetosphere, most of this energy must flow downwind through the magnetosphere and will not contribute to the storm or substorm dynamics. Considering, on the other hand, the energy conversion rate $\mathbf{J} \cdot \mathbf{E}$ in the nearest 40 R_E of the magnetotail current sheet under the assumption of a 50 kV

cross-tail potential drop a power consumption of about $3 \cdot 10^{11}$ W is found [e.g., *Stern*, 1984]. Note that this heating/energization of the inner magnetotail is not a fully independent sink of electromagnetic energy as most of this energy is carried away with precipitating particles to the ionosphere, with particle injections to the ring current, and with plasmoids and the postplasmoid plasma sheet flow back to the solar wind.

[10] One of the attractive features of the ε parameter is that it quantifies the energy input in terms of power and this power is calibrated against empirical estimates of the energy output. The same can, of course, be said of other parameters, e.g., vB_s [*Burton et al.*, 1975], once an appropriate conversion factor between the voltage and energy input is introduced. An additional positive feature is the smooth functional dependence on θ which allows weak energy input also during northward IMF ($\theta = 0$ is a singular state which never takes place over significant periods). Because the magnetospheric response involves several timescales, e.g., temporary magnetic energy storage in the tail lobes from where it is released in the substorm process, the total energy budget can be investigated by integrating the input over the time period of interest and comparing this to the energy consumed in various parts of the magnetosphere, also computed as time integrals of power consumption/dissipation. This way we can treat the net energy output on the different storm and substorm timescales, including also the intermittent plasmoid releases.

[11] The ε parameter has turned out to be a very useful tool in energy analysis and has survived unmodified a period of 20 years of increasing understanding of magnetic storms and magnetospheric substorms. Unfortunately, the users of the parameter do not always seem to have made it clear to themselves what is the physical context of the parameter. For example, the ε parameter is sometimes understood to describe the upstream solar wind Poynting flux transfer to the magnetosphere, or the scaling factor $(7 R_E)^2$ in the definition of the parameter as the effective area of the solar wind-magnetosphere interaction. Furthermore, on the time-scales of storms and substorms the time-dependence of the coupling process is an issue as it is not clear that the parameter l_0, whatever its physical meaning is, would be constant.

[12] The aim of the present discussion is not to criticize the parameter ε itself. *Akasofu* [1981] made it very clear that the parameter should be considered as a first approximation for the solar wind-magnetosphere coupling function and also reminded of the great uncertainty of the various formulas used to derive the quantitative estimates for energy output. Instead we attempt to give some clarity to the foundations of the parameter and to warn against its uncritical or sloppy usage in scientific work. We begin the analysis with a review of the definition of the parameter and the underlying dimensional analysis. Thereafter we consider the problems related to energy conversion and finally discuss some recent studies of energy output to various energy sinks.

2. Epsilon Parameter

2.1. Questions Arising From the Definition of ε

[13] The epsilon parameter was introduced in a paper by *Perreault and Akasofu* [1978]. They expressed the interplanetary energy flux in terms of Poynting flux and found a relationship between this quantity and the energy consumption in the inner magnetosphere. Consequently, they wrote the parameter as

$$\varepsilon = \frac{|E||B|}{4\pi} \sin^4\left(\frac{\theta}{2}\right) l_0^2. \tag{3}$$

For l_0 they found the thereafter invariably used value 7 R_E.

[14] Note that this expression is not in standard cgs-Gaussian nor in SI units, where the Poynting vector is $\mathbf{S} = (c/4\pi)\mathbf{E} \times \mathbf{B}$, or $\mathbf{S} = \mathbf{E} \times \mathbf{B}/\mu_0$, respectively. Instead the equations given by *Perreault and Akasofu* [1978] appear to be in the emu or esu system (for conversions between the unit systems see, e.g., *Jackson* [1975]). In these units the electric field in equation (3) is transformed by $E = vB$ and we get the expression

$$\varepsilon = \frac{vB^2}{4\pi} \sin^4\left(\frac{\theta}{2}\right) l_0^2 \tag{4}$$

which is a factor of 4π smaller than the widely used expression (1). However, both *Perreault and Akasofu* [1978], using expression (3), and *Akasofu* [1979], using expression (1) seem to have derived same numerical values in units of power (erg s^{-1}) using the same l_0. As the proper absolute value of the Poynting vector in terms of speed and magnetic field in both Gaussian and emu systems is $vB^2/4\pi$, the factor of 4π can be interpreted to have been hidden in the scaling factor l_0^2 in expression (1).

[15] The same happens, of course, in the SI units. If this is not taken into account, the calculated input powers are about one tenth of those which have been found considering the various output channels. In such a case, practically all energy budget analyses based on the ε-parameter would meet a severe energy crisis.

[16] There is another problem related to the simple Poynting flux picture. The Poynting vector is always perpendicular to the magnetic field. In the extreme case of the IMF directed along the direction of the solar wind speed there is no electric field nor any Poynting vector toward the Earth. In order to calculate the component of the Poynting vector toward the Earth we must first take the cross product between the electric and magnetic fields and only thereafter the absolute values. Let us assume, for simplicity, that the solar wind velocity is in the $-x$-direction (toward the Earth). Then the component of S in that direction is

$$S_x = \frac{(\mathbf{E} \times \mathbf{B})_x}{\mu_0} = \frac{v_x\left(B_y^2 + B_z^2\right)}{\mu_0} = \frac{v_x B_T^2}{\mu_0}. \tag{5}$$

[17] Note, however, that *Perreault and Akasofu* [1978] did not make any direct claims of transfer of upstream Poynting flux to the magnetosphere. This concept was first proposed by *D'Angelo and Goertz* [1979] and later discussed in more detail by *Pudovkin et al.* [1986]. However, the penetration of Poynting vector field lines from the upstream solar wind through the magnetosheath and magnetopause into the magnetosphere does not provide an adequate description of energy transfer as discussed in section 3.

[18] A further point of confusion is related to the definition of the angle θ and whether the magnetic field dependence should be B^2 or B_T^2. The angle is defined in the *y-z* plane, but the direction of the *y*-axis, i.e., the equatorial plane, has to be defined. The GSM coordinate system is the evident choice as in these coordinates $\theta = 180°$ corresponds to the direction exactly antiparallel with respect to the geomagnetic field at the subsolar magnetopause. Note, however, that θ is just a variable in the definition of the ε parameter, which can be defined from the upstream observations. The actual shear angle at the magnetopause is a much more complicated issue because one has to consider the magnetosheath flow draping the magnetic field around the magnetopause [e.g., *Kallio and Koskinen*, 2000]. That the angular dependence of the form $\sin^4(\theta/2)$ is reasonable in terms of an MHD reconnection picture has been discussed by several authors [e.g., *Kan and Lee*, 1979; *D'Angelo and Goertz*, 1979; *Pudovkin et al.*, 1986].

[19] In the original definition and in most practical magnetospheric energy budget studies the ε parameter is computed using the total magnetic field whereas there are strong theoretical arguments that one should use B_T that is defined in the *y-z* plane. As noted in equation (5), only B_T contributes to the Poynting flux toward the Earth. At the shock and in the magnetosheath $|B_T|$ is strongly enhanced whereas the component along the flow direction is affected only weakly. Consequently, *Vasyliunas et al.* [1982], *Kan and Akasofu* [1982], and several other subsequent theoretical studies have considered the ε parameter where B^2 has been replaced by B_T^2. As will be discussed in section 5, however, empirical studies give inconclusive results of this issue.

2.2. Dimensional Analysis

[20] The dimensional reasoning that the upstream electromagnetic energy flux density would be an appropriate input function is not based on rigorous dimensional analysis. *Vasyliunas et al.* [1982] discussed the energy transfer from a general dimensional analysis point of view, describing the MHD flow, coupling to a resistive ionosphere, and viscous interaction on the magnetopause. Neglecting the roles of viscous interaction and the ionospheric load they found that a general form of energy transfer rate is

$$P = M_E^{2/3}\mu_0^{1/3-\alpha}B_T^{2\alpha}\rho^{2/3-\alpha}v^{7/3-2\alpha}G(\theta) \tag{6}$$

where M_E is the strength of the dipole moment of the geomagnetic field M_E, B_T is the solar wind magnetic field perpendicular to the Sun-Earth line, ρ is the solar wind mass density, and $G(\theta)$ is a dimensionless function describing the dependence on the orientation of B_T and including a numerical factor to be determined from observations. Equation (8) is based upon the assumption that the energy transfer rate has a power law dependence on the upstream Alfvénic Mach number (M_A) with a slope of -2α. Introducing the Chapman-Ferraro scale length as

$$l_{CF}^6 = \frac{M_E^2}{\mu_0\rho v^2} \tag{7}$$

$M_E^{2/3}$ can be replaced by l_{CF}^2 in the expression of power

$$P = \mu_0^{2/3-\alpha}l_{CF}^2B_T^{2\alpha}\rho^{1-\alpha}v^{3-2\alpha}G(\theta). \tag{8}$$

[21] Note that in addition to the numerical factor in the function $G(\theta)$, α is a free parameter that has to be found empirically. According to the analysis of *Vasyliunas et al.* [1982], the two most widely used coupling functions vB_s and ε can be related to equation (8) by considering their dependence on B_T. If the dependence is assumed to be linear as in vB_s, $\alpha = 1/2$ and the power can be written as

$$P_1 = \mu_0^{1/6}l_{CF}^2vB_T\left(\rho v^2\right)^{1/2}G(\theta). \tag{9}$$

If the dependence is quadratic as in ε, $\alpha = 1$, and the power formula reads as

$$P_2 = \mu_0^{-1/3}l_{CF}^2vB_T^2G(\theta). \tag{10}$$

Thus the rigorous dimensional analysis has introduced a dependence on the variable Chapman-Ferraro scale length l_{CF}^2. In the case of vB_s there is an additional dependence on the square root of solar wind dynamical pressure and in total equation (9) depends on the solar wind pressure as $(\rho v^2)^{1/6}$, whereas the expression (10) depends on $l_{CF}^2 \propto (\rho v^2)^{-1/3}$. In both cases the dimensional analysis thus suggests that the energy input also depends on solar wind density, although not very strongly.

[22] In a paper accompanying the dimensional analysis by *Vasyliunas et al.* [1982], *Kan and Akasofu* [1982] argued that ε is a good first-order approximation to the input power as one can replace l_{CF}^2 by the constant l_0^2. After all, the numerical value of l_0 is determined by estimating the actual output power in the magnetosphere and can be modified accordingly.

[23] Recently, *Stamper et al.* [1999] revisited the dimensional analysis in their search for an ideal coupling constant on the long timescales between the annually averaged solar wind parameters and the annually averaged *aa* index. Their strategy was to look for the value of α that gives the best correlation. The highest correlation coefficient 0.94 was found for $\alpha = 0.386$. This is a high correlation, indeed. It clearly supports two strong assumptions in the analysis by *Vasyliunas et al.* [1982]: First, only one parameter is needed to describe the magnetosphere, i.e, the magnetic dipole moment, which on these timescales can be considered constant. Thus on the long timescales the magnetosphere processes the solar wind input in a constant manner. Second, finding such a high correlation coefficient lends strong support to the assumption that the energy transfer scales as $M_A^{-2\alpha}$, i.e., it has a power law dependence on the upstream Alfvén Mach number.

[24] Note, however, that such long timescales are of less interest in studies of storms or substorms as the detailed physical conditions of the regions where the energy is either dissipated or used in particle energization are of interest. Individual storms and substorms are quite different from each other and the physical similarity of isolated substorms and storm time substorms is still an open issue.

[25] In the analysis by *Vasyliunas et al.* [1982] discussed above the ionospheric effects were neglected motivated by the prevailing understanding at that time that the ionosphere was a minor energy sink (some 10% of the total). As discussed in section 4 below, recent studies do not support this assumption any more. However, the general formula-

tion of *Vasyliunas et al.* [1982] included also the height-integrated ionospheric Pedersen conductivity Σ_P as an independent ionospheric variable. In such a case $H = \mu_0 \Sigma_P v$ is another dimensionless variable, and instead of considering the energy transfer function of the form $F(M_A^2, \theta)$ as in the derivation of equation (8), the transfer function would now be of the form $F(M_A^2, H, \theta)$. Assuming that the input power has a power law dependence also on H with the slope $-\beta$, equation (8) is modified to

$$P_3 = C \cdot B_T^{2\alpha} \rho^{2/3-\alpha} v^{7/3-2\alpha-\beta} \Sigma_P^{-\beta} G(\theta) \tag{11}$$

where the dimensional constants (M_E, μ_0) are included in the (α-dependent) constant C. If Σ_P is approximated by a constant, e.g., by its average value over the period investigated, the only difference from equation (8) in the functional form is the power of $-\beta$ in the dependence on solar wind speed.

[26] An optimal combination of α and β can, in principle, be found by multiple regression analysis. However, until we have more exact methods than we do today of calculating the output for a large number of events, it is questionable if such a procedure would lead to a successful result.

2.3. Effective Area of Interaction

[27] As noted in the introduction, the parameter l_0^2 is sometimes interpreted as the effective cross-sectional area, either the area through which the solar wind Poynting flux is transferred to the magnetosphere or the fraction of the transfer area normalized by the efficiency of the transfer. However, as the factor of 4π is hidden in l_0^2, a more appropriate way of defining the effective area would be to consider an area A_{eff}, defined as

$$\varepsilon = \frac{vB^2}{\mu_0} \sin^4\left(\frac{\theta}{2}\right) A_{eff} \tag{12}$$

where

$$A_{eff} = 4\pi l_0^2 \approx \pi (14\ R_E)^2 \tag{13}$$

which corresponds to $l_0 \approx 7\ R_E$ in the common formulation of the ε parameter. That is, the cross-sectional area from which all electromagnetic energy flux is needed to balance the energy dissipation in the magnetosphere corresponds to a circle with the radius of 14 R_E. This is surprisingly close to the radius of the magnetopause at the terminator. However, this looks like a mere coincidence without a physical basis.

[28] Now the straightforward replacement of l_{CF}^2 by l_0^2 introduces a problem in the case of large solar wind pressure. We find it counterintuitive to think that increasing pressure would reduce energy input although this could be explained as a result of reduced interaction area. Note that this is not an issue with P_1 (equation (9)), where the additional solar wind pressure factor $(\rho v^2)^{1/2}$ makes the coupling function increase with the pressure. What finally happens with P_2 (equation (10)) depends on the actual changes of the density and velocity of the solar wind. Assuming constant velocity P_2 decreases with increasing density, but if the velocity and density are anticorrelated so that ρv is constant, also P_2 increases with increasing velocity, and thus pressure. Consequently, it is not enough to consider the solar wind pressure alone, but both density and velocity need to be taken into account as the slow-speed solar wind is typically more dense than the high-speed solar wind.

3. Energy Conversion

[29] The actual energy transfer problem is more complicated than just channeling upstream Poynting flux through the magnetopause. The strong dependence of ε on the clock-angle takes into account the dependence found empirically on the IMF north-south component in the energy transfer. During southward IMF dayside reconnection, however, consumes electromagnetic energy: part of it is used to particle acceleration and part is transformed to heat. Although different reconnection models may yield different fractions of these two conversions, the common message is that the solar wind magnetic energy flux is not transferred directly to magnetic energy in the tail lobes. It is quite possible that particles accelerated away from the reconnection line can later provide free energy for a boundary layer generator and not be lost from the energy budget, but it is questionable that the magnetic energy converted to heat in the diffusion region could be of any later use. At the first glance this appears to suggest that reconnection would require the effective radius to be larger than 14 R_E discussed in section 2.3.

[30] However, the energy transferred to the magnetosphere does not need to be of magnetic origin but is, in fact, converted from the kinetic energy of the solar wind flow. The solar wind is super-Alfvénic and the ratio of kinetic energy flux to the electromagnetic energy flux through the same area is of the order of

$$\frac{v \cdot \rho v^2}{vB^2/\mu_0} = \frac{v^2}{v_A^2} = M_A^2 \tag{14}$$

where v_A is the Alfvén velocity. For example, assuming a proton density of 5 cm^{-3}, solar wind speed of 400 km/s, and magnetic field of 10 nT (perpendicular to the velocity), the kinetic energy flux is 5×10^{-4} W/m^2 whereas the Poynting flux is 3×10^{-5} W/m^2. The corresponding fluxes through a circle with a radius of, say, 15 R_E translate to powers of 14,000 GW and 800 GW, respectively. Thus only a few percent of the kinetic energy flux through a cross-sectional area of the magnetosphere needs to be transferred into the magnetosphere in order to power storms and substorms.

[31] As the solar wind-magnetosphere interaction is a supersonic (super-Alfvénic) flow process, the formation of the bow shock is an essential part of the interaction. At the most simple perpendicular MHD shock the magnetic field increases by the factor $(\gamma + 1)/(\gamma - 1)$, where γ is the polytropic index, and the velocity decreases by the same factor. For three-dimensional adiabatic flow ($\gamma = 5/3$) the product vB_T^2 thus increases by a factor of 4, i.e., the shock is a source region of Poynting vector ($\nabla \cdot \mathbf{S} > 0$). This means that the conversion of solar wind kinetic energy to electromagnetic energy starts already at the bow shock.

[32] *Pudovkin et al.* [1986] took this fact into account and looked for a relation between the upstream epsilon parameter and the corresponding factor in the magnetosheath

close to the magnetopause. They found the Poynting flux per unit area (rewritten here in SI units)

$$F_m = \frac{v_\infty B_\infty^2}{\mu_0} \frac{\rho_m}{\rho_\infty} h l_m \sin^2(\theta_\infty - \phi_\infty). \tag{15}$$

Here ∞ refers to upstream parameters, m refers to the magnetopause, and $(\theta_\infty - \phi_\infty)$ is the angle between the IMF and the flow stagnation line at the magnetopause projected to the interplanetary space. *Pudovkin et al.* [1986] also showed that if the stagnation line is nearly parallel to the separator at the magnetopause, $\sin^4(\theta_\infty/2) \approx \sin^2(\theta_\infty - \phi_\infty)$ is a good approximation. However, this analysis does not determine the length of the stagnation line l_m nor h which the authors call the height of the "reconnection active area." The problem with this analysis is that it does not consider the actual energy transfer across the magnetopause but is merely a study of how the electromagnetic energy flux is transformed from the upstream solar wind to the magnetosheath close to the magnetopause.

[33] The energy transfer, or the conversion of magnetosheath flow energy to the magnetic energy in the magnetotail, requires the existence of a generator somewhere in the system. In the steady state Dungey-type reconnecting magnetosphere this is not a problem because there the entire high-latitude tail boundary is a generator ($\mathbf{E} \cdot \mathbf{J} < 0$), at least qualitatively. That electromagnetic energy may enter the magnetosphere far from the site where the magnetopause is opened, is nothing unphysical per se. A plate capacitor charged through a conducting wire is a simple analogue. The current carries the charges to the plate along the wire, but the electromagnetic energy stored into the capacitor can be interpreted to enter as Poynting flux inward through the space between the plates.

[34] The correct description of the dynamo in the MHD picture is that the magnetic stress at the magnetopause extracts the flow energy to the magnetic energy in the magnetosphere [e.g., *Siscoe and Cummings*, 1969; *Siscoe and Crooker*, 1974; *Gonzalez and Mozer*, 1974]. This was also the view adopted by *Kan et al.* [1980] and *Akasofu* [1981] in the context of the ε parameter. The surface stress is given by

$$T = \frac{B_n B_t}{\mu_0} \tag{16}$$

where B_n is the normal component and B_t the tangential component of the magnetic field at the magnetopause. The total power transferred through the surface A is given by

$$P = \int_A v \frac{B_n B_t}{\mu_0} dA. \tag{17}$$

This can now be equated with the Poynting flux through A because the normal component of the Poynting vector is

$$S_n = \frac{B_t E_t}{\mu_0} = v \frac{B_n B_t}{\mu_0} \tag{18}$$

where $E_t = vB_n$ is the tangential component of the electric field. Thus we see that both opening of the magnetopause ($B_n \neq 0$) and the magnetosheath flow along the magnetopause are essential to produce nonzero energy flux across the surface.

[35] A particular feature of the magnetosheath flow is that a given upstream Poynting flux tube gets focused toward the magnetopause in the plane of the magnetic field, as illustrated by *Papadopoulos et al.* [1999] who used an MHD code to trace the field lines of the Poynting vector and deviated around the magnetopause in the plane perpendicular to the magnetic field. This is a trivial consequence of the definition of the Poynting vector. Thus there is more electromagnetic energy flux toward the magnetopause in the plane of the magnetic field than perpendicular to it. However, the actual distribution of the surface stress and the magnetosheath flow velocity on the magnetopause is a more complicated problem and could only be determined by careful self-consistent global simulation that gives a sufficiently detailed description of the magnetospheric boundary. First steps toward this direction using global three-dimensional (3-D) MHD simulation are currently being made by M. Palmroth et al. (Stormtime energy transfer in global MHD simulation, submitted to *Journal of Geophysical Research*, 2002, hereinafter referred to as Palmroth et al., submitted manuscript, 2002). Note that the analyses, e.g., by *Siscoe and Crooker* [1974] or *Akasofu* [1981] operate with estimated average quantities, again leaving the coupling efficiency open, which in terms of the ε parameter means that the scale factor l_0^2 remains undetermined.

[36] The steady state picture of solar wind-magnetosphere interaction is not fully realistic and we do not know quantitatively how efficient the tail boundary is in the conversion of magnetosheath flow energy to magnetic energy in the lobes. The dissipation in the ionosphere starts to enhance soon after the southward turning of IMF and there is a clear peak in the response of the westward auroral electrojet index AL to vB_s at ~20 min [*Bargatze et al.*, 1985]. As the solar wind flows in this time ~80 R_E and as time must be allowed for the energy transfer to the ionosphere, the entry region on the magnetopause surface has to be located Earthward of this distance. Furthermore, it is unlikely that plasma and energy penetrating through the distant tail would any longer be circulated back to the main dissipation regions, ring current, and the auroral ionospheres but would flow more likely in the downwind direction in the magnetotail. Thus putting the outer limit of the calculation, e.g., at $X = -40$ R_E as was done by *Stern* [1984], seems to be a reasonable choice.

[37] The enhancement of the auroral electrojets already during the substorm growth phase further suggests that a generator may be associated more directly with the interaction process on the dayside magnetopause. Thus a realistic 3-D time-dependent solar wind-magnetosphere interaction may be a process that involves both magnetic field annihilation (reconnection) and generation (dynamo), e.g., as proposed conceptually by *Song and Lysak* [1989].

4. Use of Epsilon in Studies of Energy Budget

[38] In this section we briefly review the present estimates of the output power and/or energy. The scale factor l_0 in equations (1) and (2) was originally determined so that the input would correspond to the sum of output to ring current,

ionospheric Joule heating, and auroral precipitation. Energy carried away with the plasmoids was not considered as there were not yet good enough observations of the energy content of plasmoids. Energy dissipated through several minor channels (ion outflow from the ionosphere, auroral kilometric radiation, etc.) can be neglected in this context as they do not contribute to the total energy budget in any significant way. If we want to discuss the energy budget of storm/substorm processes, the plasmoids and the escape of the heated post-plasmoid plasma sheet must, however, be included in the calculations, or the meaning of the ε parameter should be interpreted as an energy input parameter to the inner magnetosphere only. The latter probably was the original idea of the parameter. However, *Akasofu* [1981] mentioned that there could be energy flow downwind but it should be proportional to the energy output in the inner magnetosphere due to the good agreement between epsilon and the calculated output rate. As the plasmoids nowadays are considered to be major substorm phenomena, we prefer to include the plasmoid release in the energy budget.

[39] The studies by *Perreault and Akasofu* [1978] and *Akasofu* [1981] were focused on magnetic storms of various levels and after these analyses a folklore that up to 90% of ε input would be dissipated through the ring current seems to have spread among the scientific community, although this was not explicitly suggested by the original analyses. Several subsequent studies soon after the introduction of the ε parameter indicated that the ionosphere consumes at least the same amount of energy as the ring current (for reviews, see e.g., *Stern* [1984] and *Weiss et al.* [1992]).

4.1. Epsilon Input

[40] Recently, *Tanskanen et al.* [2002a] performed an extensive study of the energy budget of 839 substorms, both isolated and storm-time events, during the years 1997 and 1999. The input was estimated using ε computed from Wind and ACE observations of the solar wind parameters. The power input was integrated over the substorm periods from the southward turning of the IMF *z*-component to the end of the recovery phase determined from ground-based magnetometer observations. The mean and median input energies for substorms were $2.9 \cdot 10^{15}$ and $1.7 \cdot 10^{15}$ J, respectively. During the largest event the input was $6 \cdot 10^{16}$ J. Note that integration of ε over the entire storm period often results in total input of more than 10^{17} J [e.g., *Knipp et al.*, 1998; Turner et al., submitted manuscript, 2002].

4.2. Ionospheric Dissipation

[41] The two main energy sinks in the ionosphere are Joule heating and auroral precipitation. Joule heating takes place through the Pedersen currents associated to the closure of field aligned-currents in the resistive ionosphere. That is, there is a net electromagnetic energy flux from the magnetosphere to the ionosphere. The precipitating energetic electrons also carry a significant amount of energy. Neither of these processes can be directly monitored continuously but both of them have been shown to be related to the strengths of the auroral electrojets and several empirical relations between the auroral electrojet indices and the dissipation have been derived (for reviews, see *Weiss et al.* [1992] and *Lu et al.* [1998]).

[42] *Tanskanen et al.* [2002a] used in their study of 839 substorms the longitudinal IMAGE magnetometer chain from southern Finland to Svalbard. They calculated a local westward electrojet index *IL* (expressed in nanoteslas) which was then converted to a proxy Joule heating rate (expressed in watts) over the Northern Hemisphere as

$$U_J(\mathrm{W}) = 3 \cdot 10^8 IL(\mathrm{nT}) \tag{19}$$

following *Ahn et al.* [1983] (see also discussion by *Lu et al.* [1998]). The Joule dissipation rate was integrated over the substorm periods.

[43] Although the Northern and Southern Hemispheric dissipation rates most likely are not equal, we multiply the obtained dissipation by two to get a first approximation to the total Joule dissipation. From the *Tanskanen et al.* [2002a] study we get for the total Joule heating output the average value of $1.3 \cdot 10^{15}$ J and the median value of $0.9 \cdot 10^{15}$ J, the highest Joule dissipation event yielding $8 \cdot 10^{15}$ J. Thus we can take 10^{15} J as a representative value for substorm energy dissipation through $\mathbf{E} \cdot \mathbf{J}$ in the ionosphere.

[44] The dissipation through electron precipitation has traditionally been considered to be significantly less than the Joule heating. For example, *Ahn et al.* [1983] estimated the dissipation rate to be 20% of Joule heating plus a constant offset of 12 GW to account for the continuous diffuse precipitation. This view has recently been challenged by *Østgaard et al.* [2002] who derived new proxies based on the X-ray imager PIXIE and the ultraviolet imager UVI onboard Polar. They argued that the deposition rate is proportional to the square root of *AE* or *AL* and found the best fitting formulas

$$U_A(\mathrm{GW}) = 4.6\sqrt{AE(\mathrm{nT})} - 23 \tag{20}$$

$$U_A(\mathrm{GW}) = 4.4\sqrt{AL(\mathrm{nT})} - 7.6 \tag{21}$$

where *AE* and *AL* are given in nanoteslas and the power is gigawatts. If we replace *AL* by *IL*, we find that for the typical substorm of *Tanskanen et al.* [2002a] the energy dissipation through electron precipitation is $0.6 \cdot 10^{15}$ J, that is about 2/3 of the Joule dissipation.

4.3. Ring Current

[45] As discussed by *Tanskanen et al.* [2002a], ionospheric dissipation consumes a larger portion of the ε input during isolated substorms than during storm-time events. Although the treatment of storm time substorms is more difficult and uncertain than of isolated substorms owing to the problems related to the subjective selection of start and end times of the integration periods, this is a reasonable result as during isolated substorms the energy output to the ring current is expected to be small. However, several recent studies indicate that the ionosphere may be the dominant energy sink also during storm periods. In a comprehensive study of the early November 1993 storm, *Knipp et al.* [1998] estimated the energy dissipated by the ring current, Joule heating, and precipitation using the AMIE technique. They found that throughout the storm the energy (i.e., integrated power) consumed by the Joule heating was more than 50% of the total consumption of these three dissipation

channels. The ring current was more efficient than precipitation only during the main phase of the storm but even there less efficient than the Joule heating. A similar result was found for the January 1997 storm by *Lu et al.* [1998] also using the AMIE procedure.

[46] The energy partitioning during storms was analyzed by Turner et al. (submitted manuscript, 2002) using both the *Dst* index and direct ring current particle observations by the CAMMICE instrument onboard Polar during six storms in 1997–1998. They estimated that Joule heating accounts for ~50% or more of the storm time energy dissipation, whereas the ring current accounts only for 10–15%. If we scale this to the typical substorm Joule dissipation of 10^{15} J, we find that the energy consumption in the ring current would be at most $(0.2–0.3) \cdot 10^{15}$ J. Note that for isolated substorms the ring current dissipation can be negligible, i.e., at the same level as during quiescent magnetospheric conditions.

[47] An essential reason why the Turner et al. (submitted manuscript, 2002) results for ring current were smaller than traditional estimates was that they reduced, by a factor of 2, the widely used [e.g., *Akasofu*, 1981] formula

$$U_{RC} = -4 \cdot 10^{13} \left(\frac{\partial Dst}{\partial t} + \frac{Dst}{\tau} \right) \tag{22}$$

to convert the *Dst* index to power consumption in order to account for the tail current contributions and induction effects in the determination of the *Dst* index. However, even without this modification, the ring current dissipation remains smaller than the ionospheric Joule dissipation.

[48] While these results are fresh and need to be confirmed by subsequent studies, it is evident that the simultaneously increasing estimates of the ionospheric dissipation and decreasing estimates of the ring current dissipation have turned the relative roles of the output channels upside down.

4.4. Plasmoids and Escape of Plasma Sheet

[49] As we argued above, the energy carried by plasmoids is essential in substorm dynamics and should be included in the energy budget considerations. *Ieda et al.* [1998] investigated 824 plasmoid events in the Geotail data set. They found that the energy carried by individual plasmoids varied with the distance from the Earth, being $0.16 \cdot 10^{15}$ J in the midtail region. Taking into account the finding by *Slavin et al.* [1993] that, on average, 1.8 plasmoids are released per each substorm, *Ieda et al.* [1998] concluded that on average, the energy carried by plasmoids would be $0.3 \cdot 10^{15}$ J. However, they noted further that this is not all energy flowing out with the plasma sheet. They estimated the energy flux in the heated postplasmoid plasma sheet was twice as much as the plasmoid energy, and thus a typical substorm energy release in the down-tail direction would also be of the order of 10^{15}, i.e., about the same as the Joule dissipation in the ionosphere.

5. Is There Need for Revision of the ε Parameter?

[50] The typical figures of Joule dissipation, electron precipitation, ring current, and plasmoids in the previous section sum up to $(2–3) \cdot 10^{15}$ J per substorm, depending on how reliable we consider the new estimates of precipitation and postplasmoid plasma sheet energies to be. As we have taken the median value of the Joule dissipation as a representative number, the output compares well with a typical input of $\sim 2 \cdot 10^{15}$ J. Considering all uncertainties in the original determination of l_0, this is still a remarkably good order-of-magnitude correspondence. Assuming, however, that the estimates of *Østgaard et al.* [2002] for the energy carried by precipitation and of *Ieda et al.* [1998] for postplasmoid plasma sheet are correct, the epsilon input seems to be somewhat too small.

[51] It is interesting to note that the analysis by *Perreault and Akasofu* [1978] implies that in 10 of the 15 storms analyzed the epsilon parameter integrated over the storm period (of the order of 10^{16} J) was smaller than the estimated energy consumption and the smallest ratio was 0.4.

[52] The comprehensive AMIE studies [*Knipp et al.*, 1998; *Lu et al.*, 1998] also indicate that the integral of the parameter (equations (1) and (2)) remains below the total energy consumption. *Knipp et al.* [1998] note that this may be due to incomplete coverage of the solar wind data. As they, on the other hand, may have underestimated the substorm related output during the early phase of the storm, the conclusion that remains below the total dissipation is most likely true. There is, however, no need to look for an explanation in the solar wind data as already the scaling of ε is uncertain.

[53] As discussed in section 2.1, in most energy budget studies the ε parameter is computed without first subtracting the IMF x-component. For the $B_z = 0$ case B^2 is, on the average, a factor of 2 larger than B_T^2, as the Parker spiral angle is ~45°. Of course, as the energy input is most efficient when there is a strong southward B_z, the effect of including or neglecting B_x may often be smaller but can, in principle, also be larger, for example, when $B_Y \approx 0$, $|B_x| > |B_z|$. One may argue that B_T^2 would be a more physical parameter but the empirical analyses have given inconclusive results on this issue. For example, in the neural network analysis by *Wu and Lundstedt* [1997] the predictions of the Dst index with the classic epsilon were, in fact, much better than with the parameter where B^2 was replaced with B_T^2. *Tanskanen et al.* [2002b] noted that using B_T^2 moves some outlier events in their substorm statistics but does not give improved energy input-output correlation when integrated over the substorm periods. However, they demonstrated that in individual cases with a large B_x, such a substorm on 17 December 1997, the relative weakness of the ionospheric output with respect to epsilon input may be a result of the fact that the upstream B_T^2 has more control on the magnetospheric energetics than B^2.

[54] In summary, most present studies point toward a slight increase of the epsilon parameter. A factor of 1.5 seems to be quite enough and it is unlikely that more than a factor of 2 would be needed.

6. Conclusions

[55] Considering that there is no rigorous physical derivation of the epsilon parameter, that dimensional analysis does not uniquely determine its functional form, and that its magnitude was scaled with data that have improved much during the following 20 years, the parameter, as *Perreault*

and Akasofu [1978] and *Akasofu* [1979, 1981] originally presented it, has turned out to be a very useful first order approximation for energy input to the magnetosphere.

[56] While useful in practical studies, the unclear physical foundation of ε has sometimes led to the misinterpretation that it would be a measure for transfer of solar wind Poynting flux to electromagnetic energy in the magnetosphere or that the scaling parameter l_0 would represent an efficient area of this transfer. A likely reason for these interpretations is a confusion between the concepts of energy supply and energy transfer function. The energy supply is the solar wind kinetic energy flow which in the super-Alfvénic solar wind is much larger than the magnetic energy flow. The kinetic power flux through a circle with a radius of 15 R_E is typically a few times 10^{13} W. The total power flux penetrating inward through the entire magnetopause is difficult to estimate but is probably a few times 10^{12} W, whereas the level of power dissipation in the substorm and storm processes is of the order of a few times 10^{11} W. Thus only a fraction of the solar wind energy needs to be transferred into the magnetosphere and only a fraction of the transferred energy is needed to power the magnetospheric dynamics.

[57] However, as *Akasofu* [1981] pointed out, the energy input into the processes in the inner magnetosphere does not scale with v^3, as the kinetic energy flux, but more like vB^2, as the electromagnetic energy flux, together with a strong dependence on the IMF clock angle. Thus the critical issue in studies of magnetospheric dynamics is not the energy supply but the transfer function to describe the free energy for the substorm and storm processes, for which ε is one of the useful first approximations. Another essential point is to understand that the total energy transferred from the solar wind includes energy needed to maintain the magnetosphere and energy dissipated by the dynamic processes in the ionosphere, the inner magnetosphere and the plasma sheet associated with the plasmoid release. Of course, energy is energy and cannot really be factorized in this way. We interpret the ε parameter as a measure of energy derived from the solar wind to power the magnetospheric dynamics, including the plasmoid release.

[58] Although the ε parameter is quite useful as it is, there are scientific reasons to look for a more fundamental description of the energy transfer. One avenue would be to improve the dimensional analysis, e.g., by including the ionospheric properties in the form of Pedersen conductance and performing multivariate analysis to determine the scaling exponents as discussed in section 2.2 above. It is, however, unclear how much real physical understanding could be acquired through such a procedure, considering the still rather rough proxies for the various output channels. Thus the ongoing studies of output estimates need definitely to be continued. Another approach would be to estimate the energy influx using global MHD calculations but even that procedure is not quite straightforward, in particular as the sufficiently exact determination of the magnetopause surface is quite difficult (M. Palmroth et al., submitted manuscript, 2002).

[59] Some obvious questions could perhaps be answered without a full physics-based quantitative description of the energy transfer process. For example, is all time-dependence in the solar wind parameters, or is l_0 variable as well, should the dependence on solar wind pressure be included, and should B^2 be replaced by B_T^2 or not?

[60] According to the recent studies discussed in section 4, the order of magnitude of l_0 seems to have survived quite all right. We suggest a revision of it from 7 R_E to 9 or 10 R_E which would increase the estimated energy input by a factor of 1.6–2.0. This would avoid any deficit in the energy budgets without increasing the input too far from realistic.

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